DIONISOS: A new experiment studying the dynamics of plasma-surface interactions

Dennis Whyte, Graham Wright, Alan Hoskinson
University of Wisconsin - Madison

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Our present lack of confidence in PSI issues primarily arises from the poor diagnosis of PSI effects

- Most of the controlling PSI physics is in hand or in a "mature" research stage
  - Physical sputtering, chemical sputtering
  - Plasma edge sheath theory
  - Atomic physics (ionization, etc.)
  - *Notable exception: ⊥ particle transport in edge plasmas*.
- By the same token, edge plasma diagnosis is mature.
- However we have essentially no direct diagnosis of how & when plasma-facing surfaces are being modified by the plasma.

The PSI diagnostic challenge

- The plasma edge is dominated by its own self-consistent recycling pattern of fuel and impurities
  - Easily implemented plasma diagnosis cannot inform us about the net surface effects (H retention, erosion, etc.)
- The lack of direct surface diagnosis cripples our ability to understand the net effects of PSI.
  - We have largely relied on surface "archeology" to inform us about surface modifications. This is unacceptable; the equivalent of basing ITER burn predictions on one-year integrated neutron fluence from JET!!)
  - Dedicated ex-situ PSI experiments (e.g. DiMES) very expensive to implement (run-time) and covers << 1% of wall surfaces.
- The challenge is to develop reliable in-situ surface diagnostic techniques that can operate in real-time and be placed in many locations.

In-situ PSI diagnosis topics

1. Erosion & deposition using quartz crystal microbalances

2. DIONISOS: Accelerator-based ion beam surface analysis experiment being developed at UW-Madison

3. Radio-isotope alpha emission for remote, in-situ “ion beam analysis” in confinement experiments.

QMB: Quartz crystal microbalances

- Measures net mass change on surface coating of a crystal by changed resonance frequency.

- **Advantages**:
  - Extremely sensitive: can measure ~mono-layer net changes in surface
  - Large dynamic range: 0.1-> 1000 nm
  - Can measure both deposition and erosion of a pre-deposited film.
  - Commercially available technology.

- **Drawbacks**:
  - No element discrimination.
  - Cannot tolerate any significant heat flux: small thermal mass.
  - Highly temperature / environment sensitive
  - Limited absolute range: ~ 1 micron << expected deposit layers.

QMB: Quartz crystal microbalances

- **Implementation needs:**
  - Special design for in-vessel electronics (ceramic based) to tolerate high baking temperatures (~ 300 C)

- **Present status.**
  - QMB successfully implemented in JET divertor…clearly demonstrating need for real-time PSI diagnosis.
  - UW-Madison, MIT and GA now collaborating on implementation of QMBs in Alcator C-Mod (Mo/B) and DIII-D (C) tokamaks.

- **Summary:** Primarily due to their intolerance to heat flux, QMBs are relegated to measuring erosion/redeposition in "hidden" areas (baffles, main-wall ports, behind tiles, etc.). Going into new DIII-D lower divertor in tile gaps.

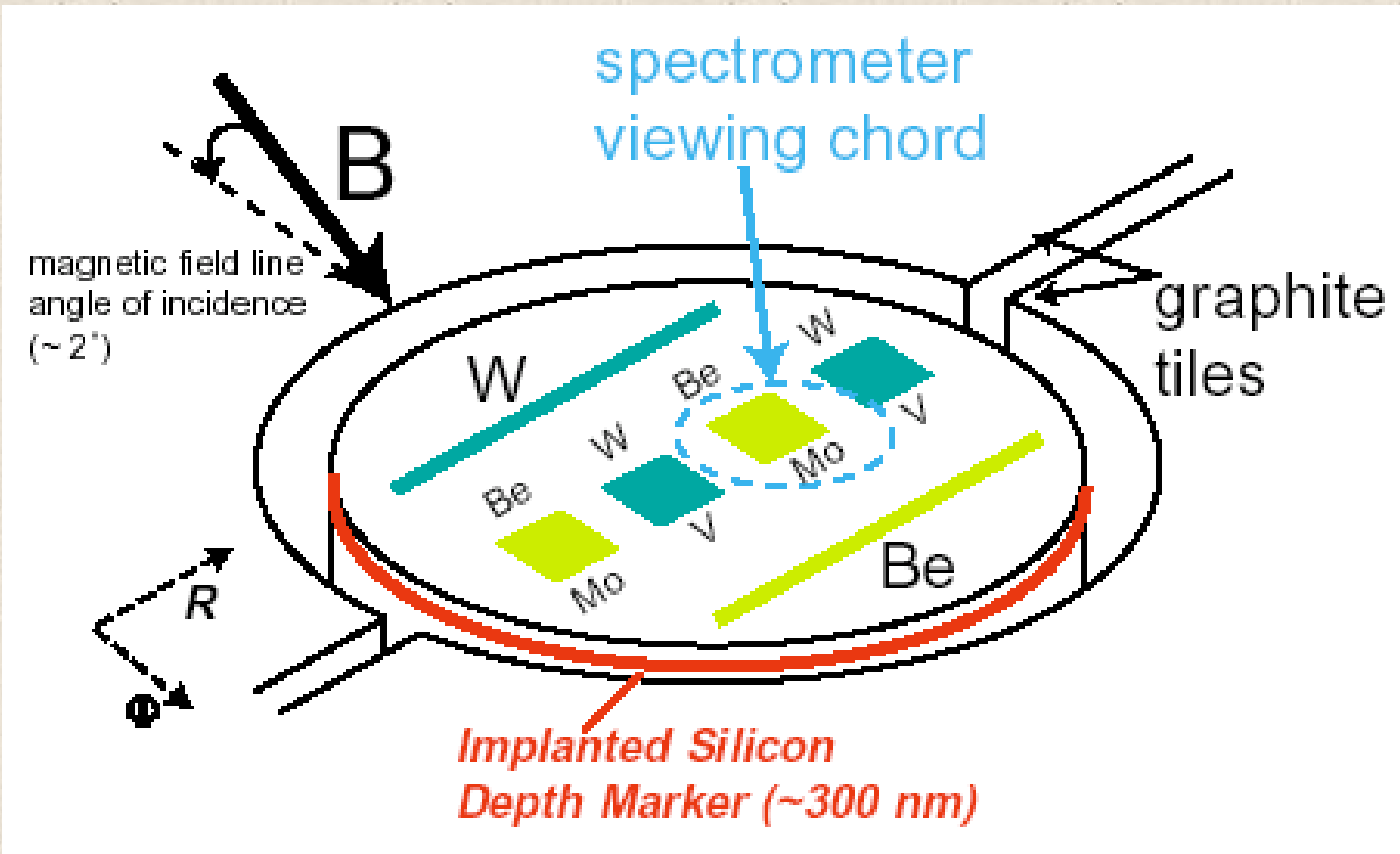
Ion Beam Analysis of Surfaces

- Interaction of ~MeV ions with surface atoms is accurately described from well-known physics
  - Rutherford elastic scattering ($M_{target}>M_{projectile}$)
  - Forward elastic recoil ($M_{target}<M_{projectile}$)
  - Inelastic nuclear reactions (all reaction σ known)
- Exploit this understanding to diagnose near-surface (~1-10 microns) properties of materials.

- **Advantages**:
  - Great flexibility: element/isotope sensitivity, erosion/deposition/H retention available in single diagnostic.
  - Measurement accuracy over appropriate depth range for PSI.
  - Proven application in fusion PSI (see examples from DiMES)
  - Simple solid-state detectors for scattered charged particles

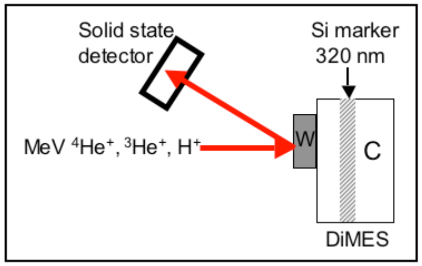
- **Drawbacks**:
  - Need ~MeV energy ions

DiMES examples of Ion Beam Analysis of Surfaces

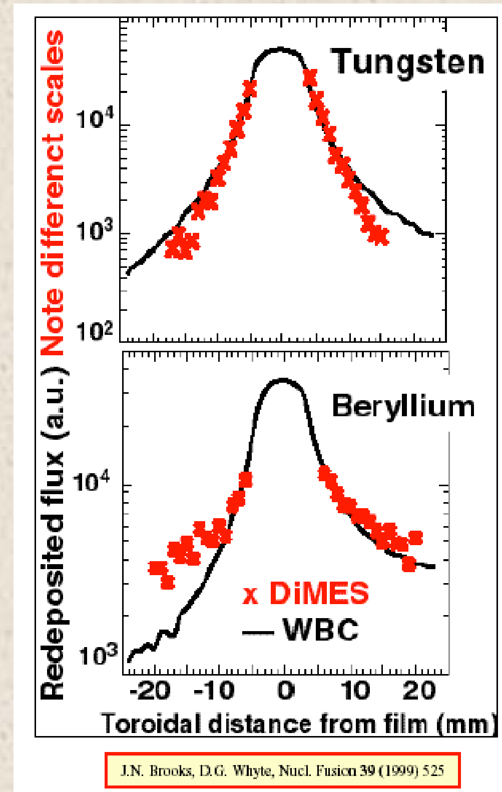


DiMES examples of Ion Beam Analysis of Surfaces

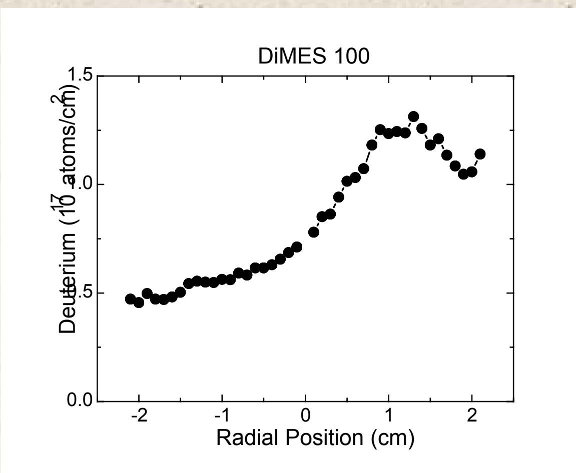
- Carbon erosion/deposition is determined by the change in depth of an implanted silicon marker measured by 2 MeV helium Rutherford backscattering (RBS). Detection limit ~ ± 10 nm.
- Metal erosion is determined from the change in thickness of thin metal films measured by RBS (W,V).
- Nuclear reaction yields give areal density of:
  - Deuterium D(^{3}He,p)α
  - Boron ^{11}B(p, α)^{8}Be



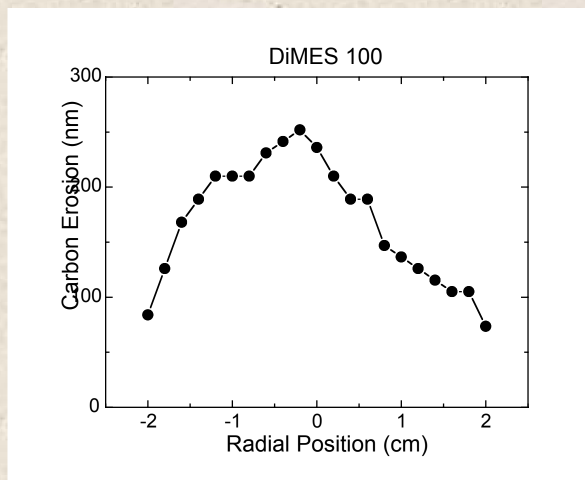
Near-surface transport



H Retention



Low-Z erosion



DIONISOS:
Dynamics of IONic Implantation & Sputtering On Surfaces

- A new experimental facility being constructed at UW-Madison.

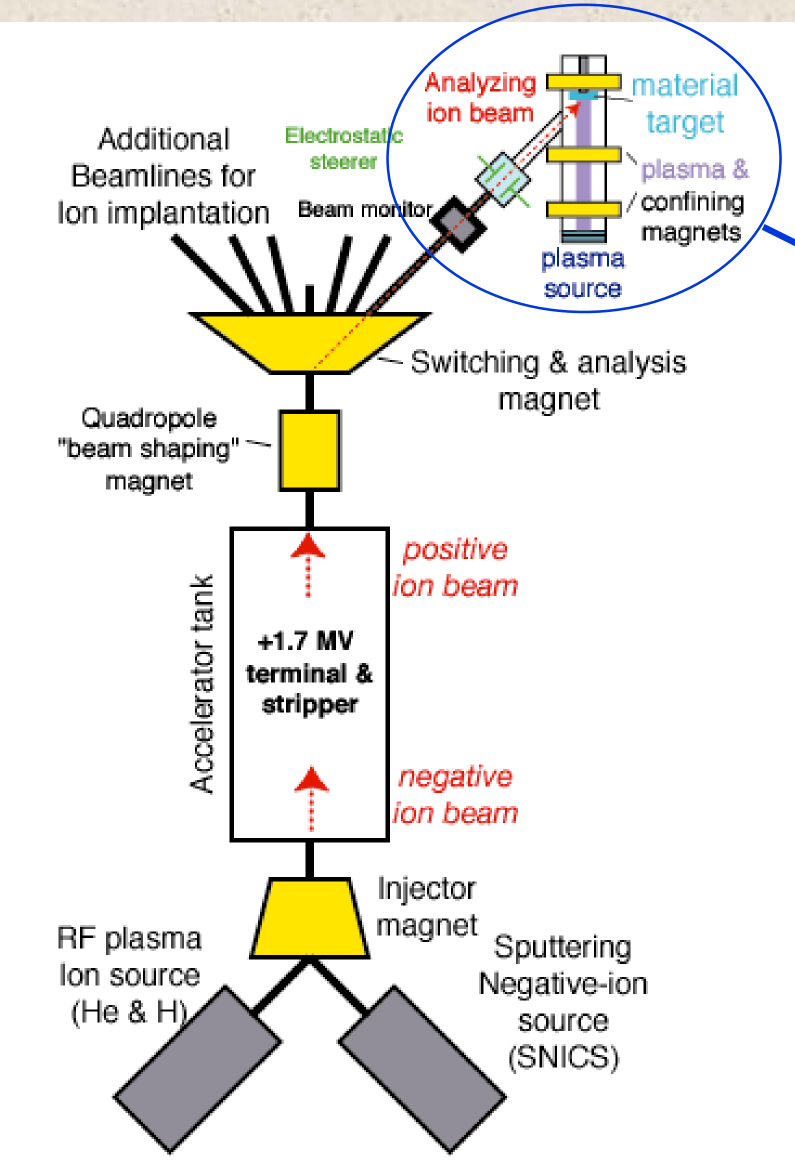
- *Goal:* Accurately measure the real-time response of the PFC material surface to plasma bombardment using in-situ high-energy ion beam analysis.

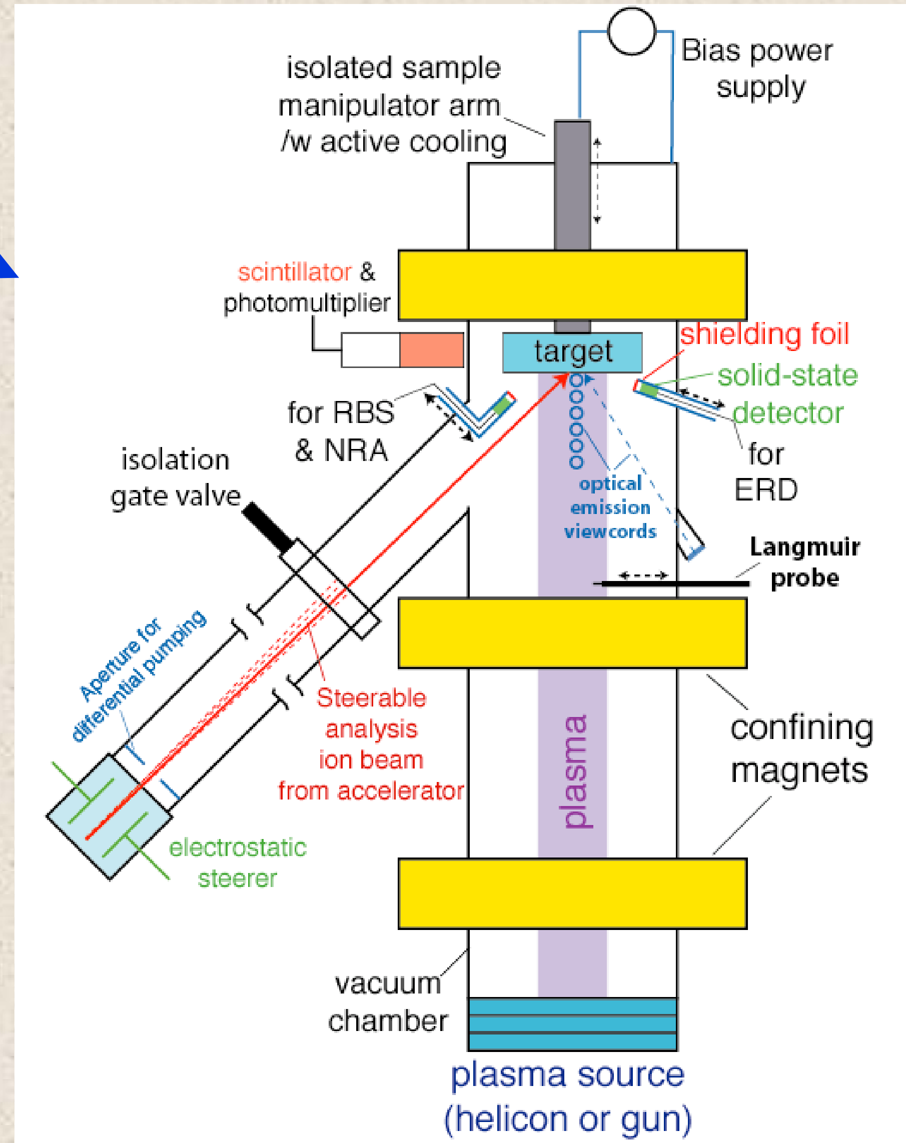
- Design philosophy:
  - Exploit ion beam analysis (IBA) techniques
    - Mature analysis tool widely used in R&D.
    - Vastly different ion energies (30 eV vs. > 1 MeV) allow for simultaneous surface interaction with little interference.
  - Use previously developed axisymmetric plasma sources
    - *Helicon:* Steady-state plasma /w good density control.
    - *Plasma gun*: high density/flux pulsed plasma source.
  - Initially focus on fusion experiments, but generic PSI tool.

Principal component of DIONISOS is now operational at UW-Madison: *1.7 MV tandem ion accelerator*

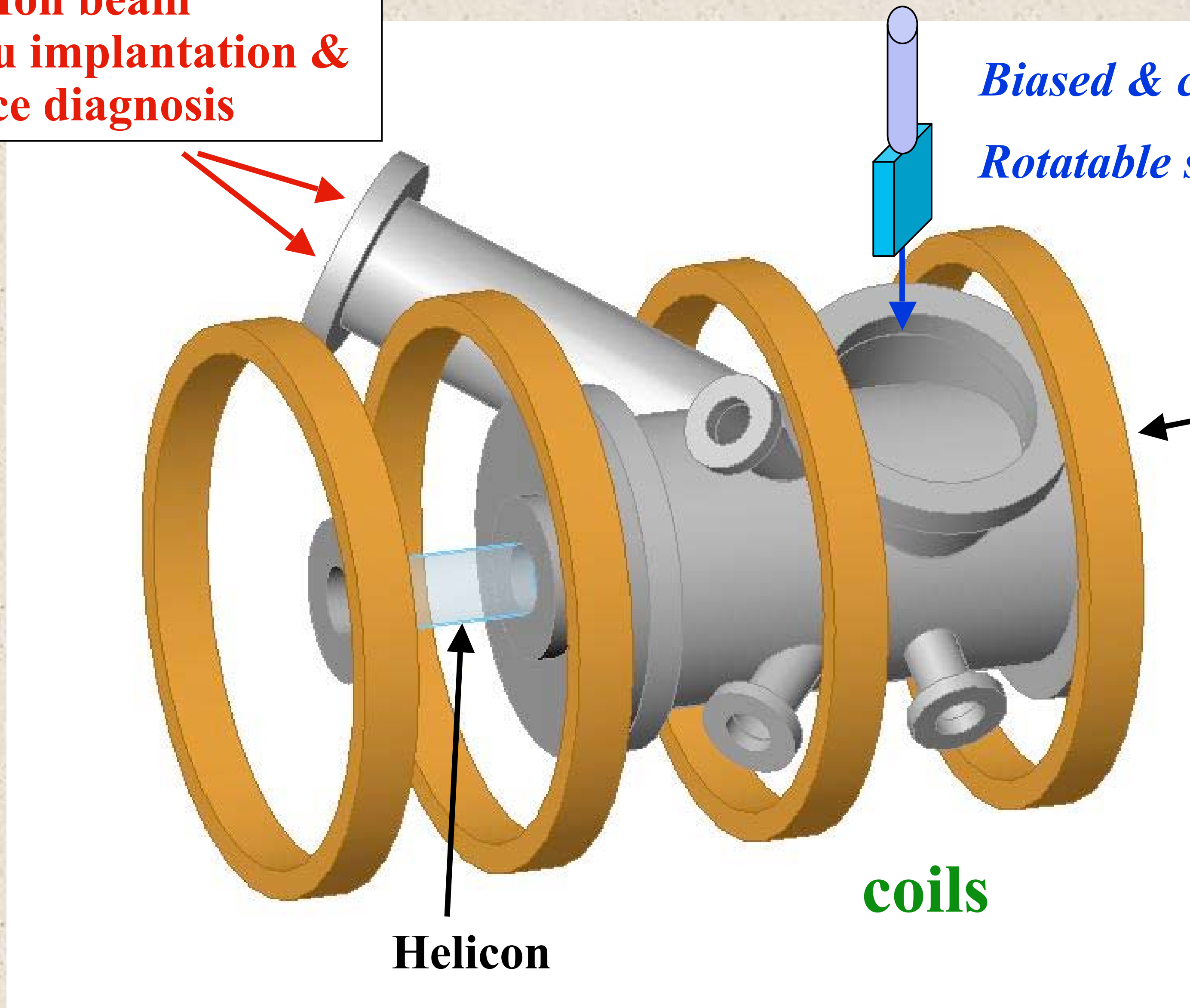
- Features:
  - Dual sources (sputtering and RF plasma), > 100 beam species available.
  - High energy (≤ 10 MeV for higher Z beams)
  - High current beamlines (> 0.1 mA) for implantation and irradiation.

DIONISOS Experiment Setup

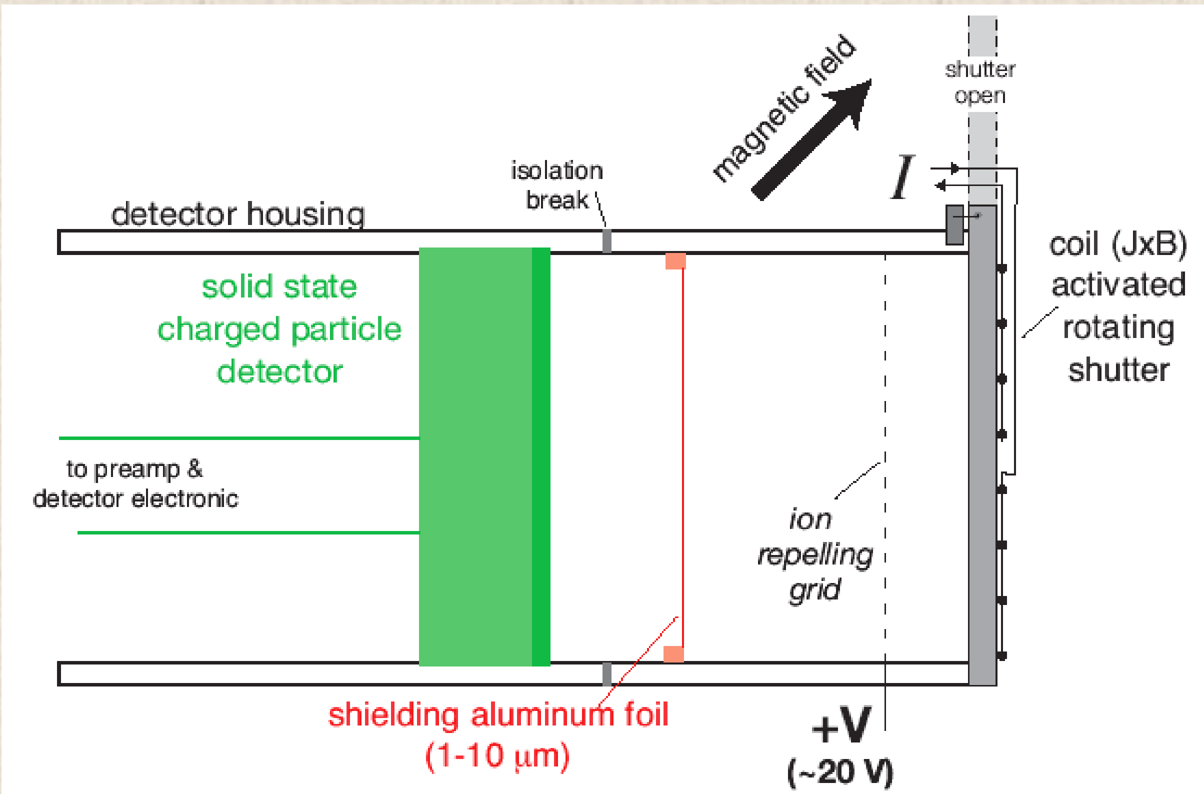




DIONISOS Experiment Setup



Experimental R&D: Development of plasma compatible ion beam analysis detector assemblies



- **Serves purpose of protecting s.s. detector from**
  - **Plasma light emission.**
  - **Low energy plasma ions.**
  - **Sputtered and CX neutrals.**

Three proposed areas of study for DIONISOS

- **Measurement and modeling of near-surface cross-field ion transport**
  - **Determine controlling parameters for the magnitude and locations of net erosion / redeposition of PFC relevant to fusion (C, W, Mo)**

- **The dynamic release of fuel and impurity particles from surfaces exposed to transient, high-density plasmas.**

- **The dynamics of hydrogenic / tritium fuel trapping in plasma-deposited films, for single and multiple species materials.**

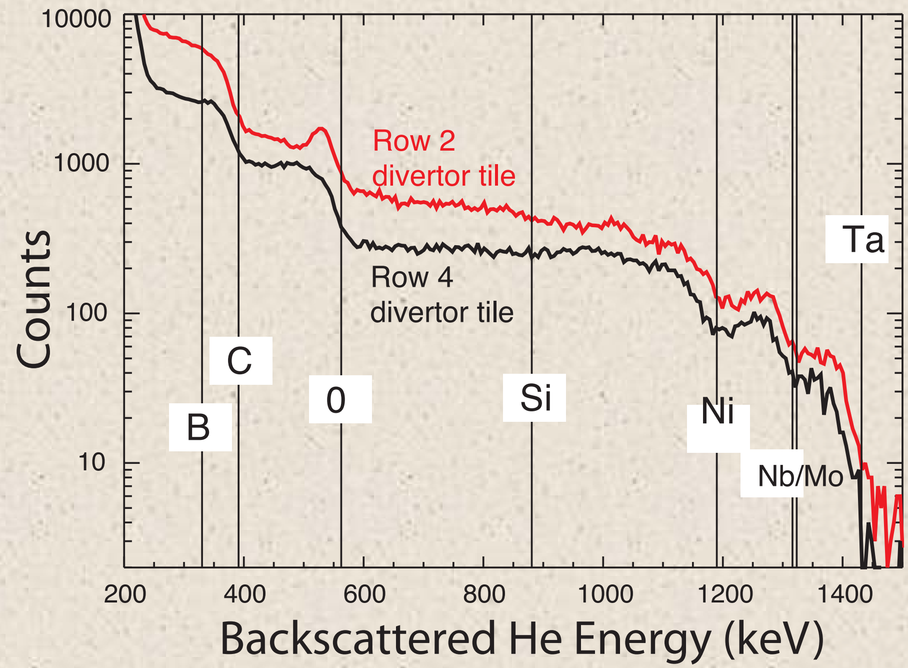
Plasma sources for DIONISOS

- **Helicon plasma source (collaboration with N. Hershkowitz)**
  - **Steady-state ionizing plasma**
  - **Solenoid field convenient linear control of plasma density**
  - **H, D, Ne, Ar**

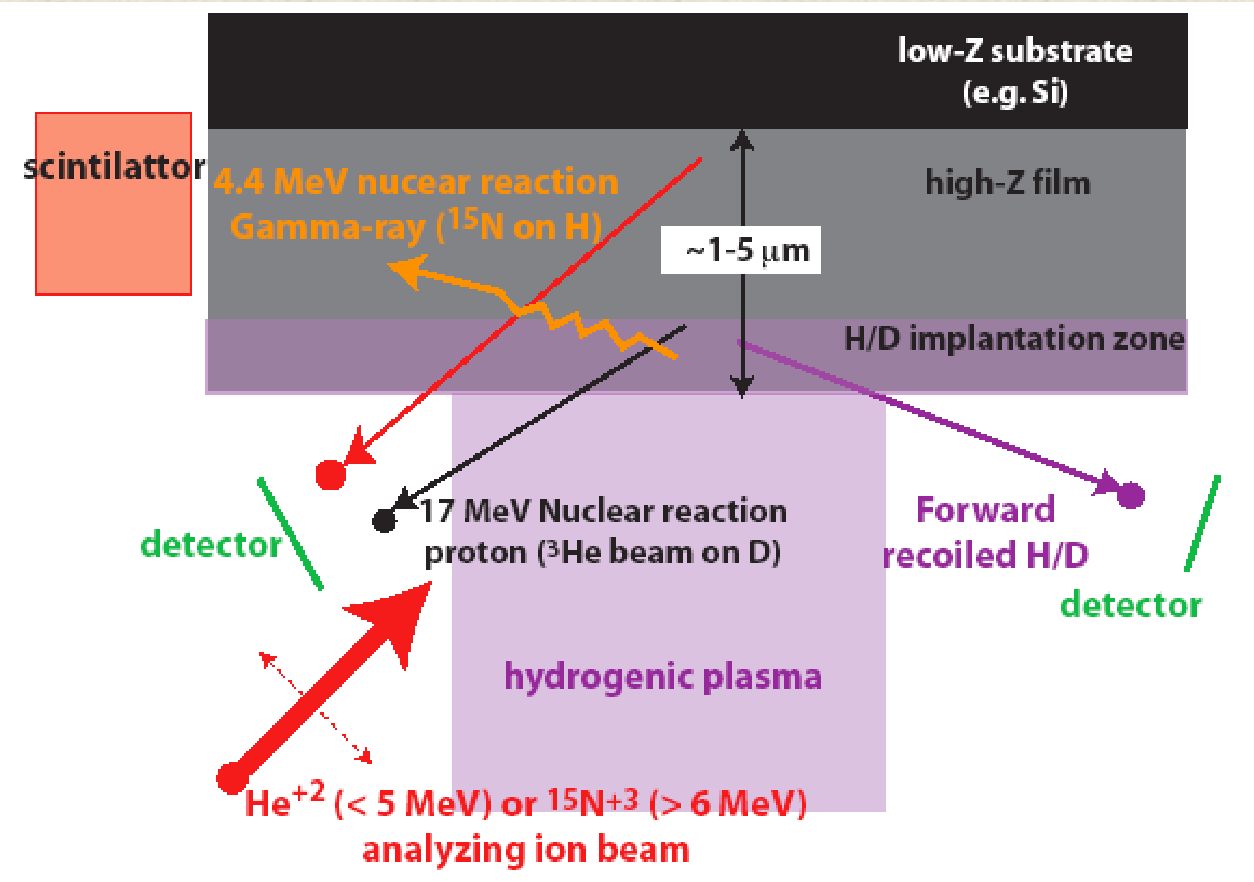
- **Plasma gun (collaboration with G. Fiksel, C. Forest)**
  - **Developed for helicity injection on MST (Fiksel et al).**
  - **Pulsed (~1-10 ms) H/D plasmas with ~60 s rep rate.**
  - **~100% ionization, T_e~20 eV high density (~10^{20} m^{-3})**
  - **~100 MW/m^2 (10 $MJ/m^2/s^{1/2}$) per 100 V bias approaches ablation/melt limits.**
  - **Capable of current densities ~ kA / cm^2**

Ion beam surface analysis tools are operational on DIONISOS

- **Rutherford Backscattering Spectroscopy**
- **Elastic Recoil Detection (H detection)**
- **Nuclear Reaction Analysis.**
- **Particle Induced Gamma Emission.**
  - Carbon-13 detection with ~2 nm depth resolution for DIII-D experiment.

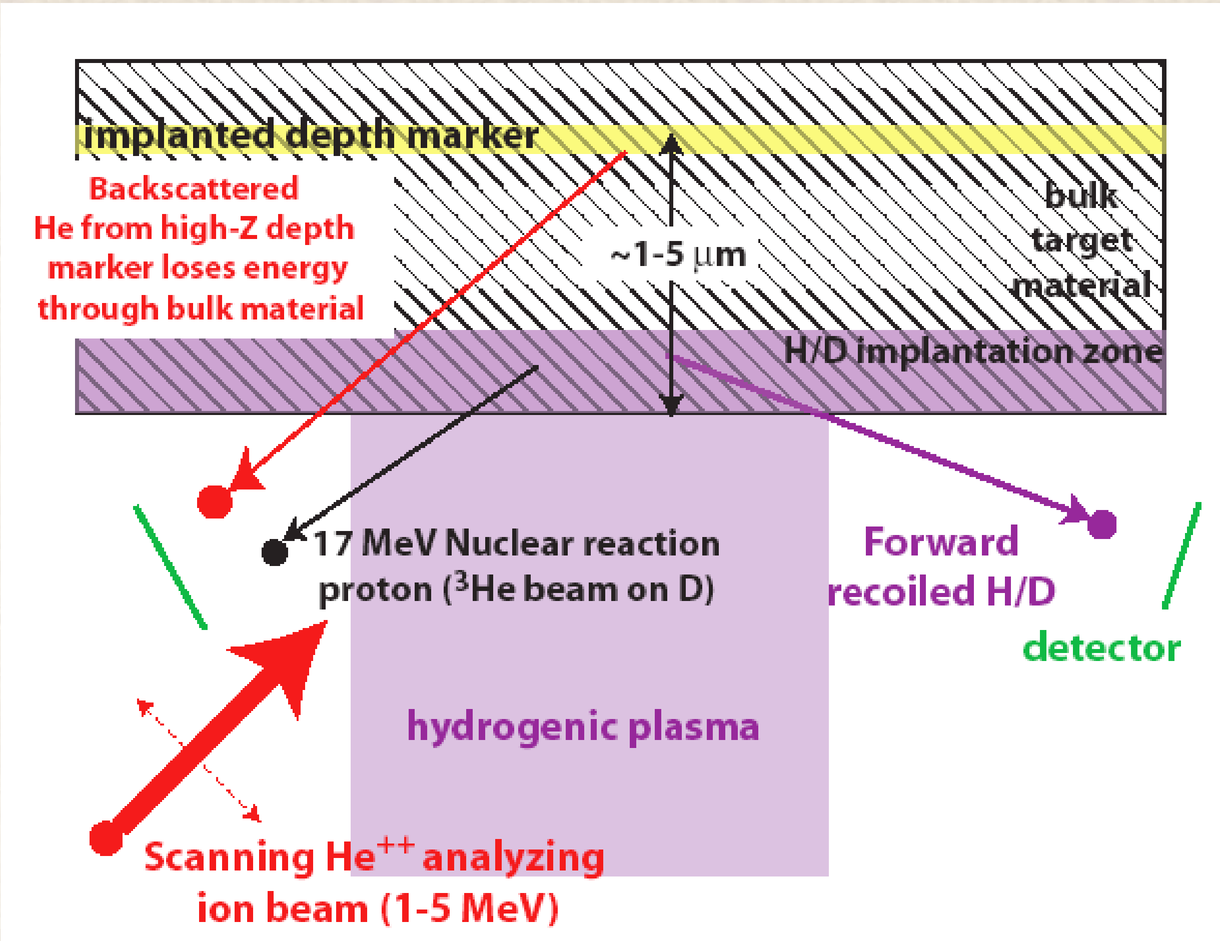


Schematic for IBA diagnosis of high-Z PFC materials



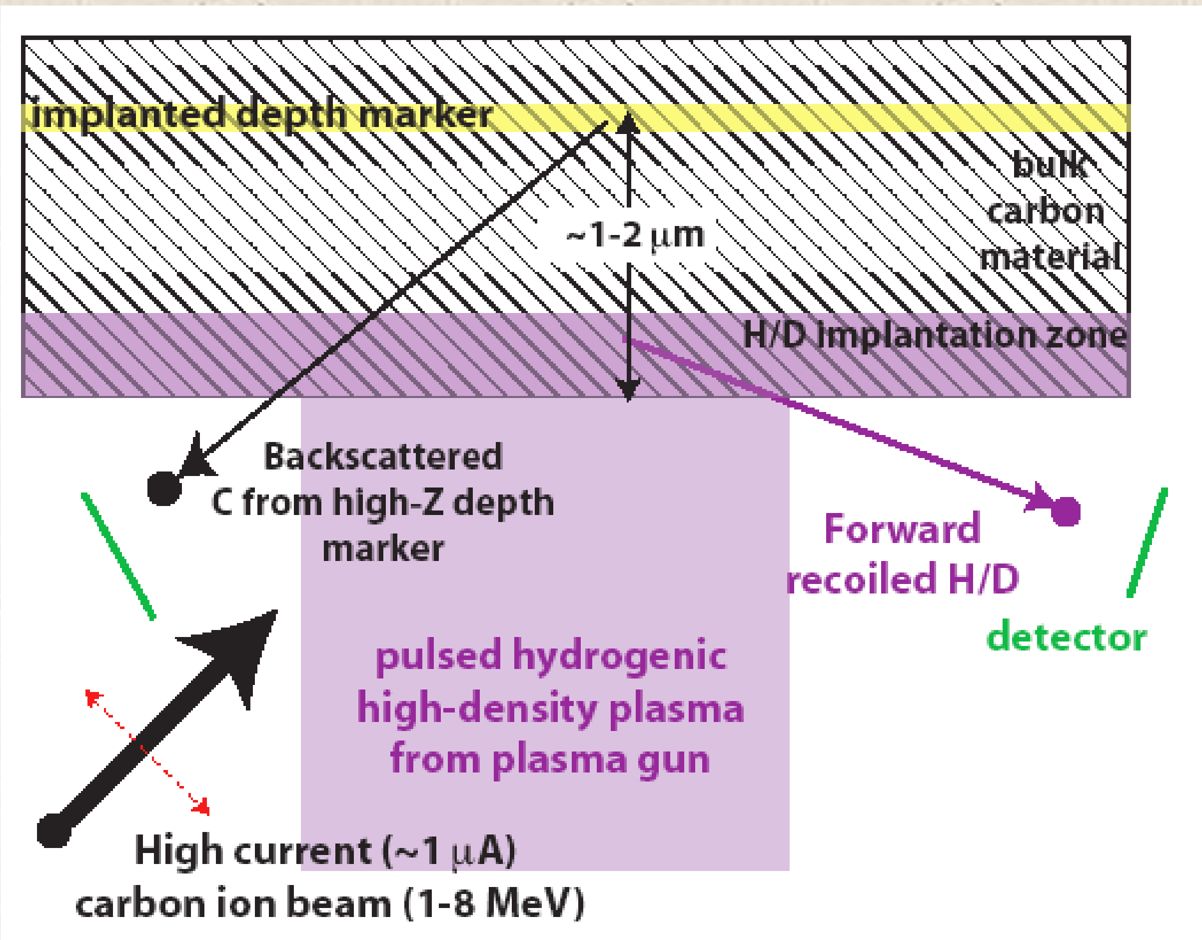
- RBS measures net erosion rate of high-Z film to ~ 5 nm.
- Forward recoil (ERD) provides depth-resolved H/D concentration.
- Highly resolved spatial profiles of isotope resolved H species with NRA.

Schematic for IBA diagnosis of low-Z PFC materials



- RBS measures net erosion rate of bulk material by changes in high-Z marker previously implanted with ion beam.
- ERD and NRA provide real-time hydrogenic concentrations and diffusion in deposited films

Schematic for IBA diagnosis of H dynamics in PFC

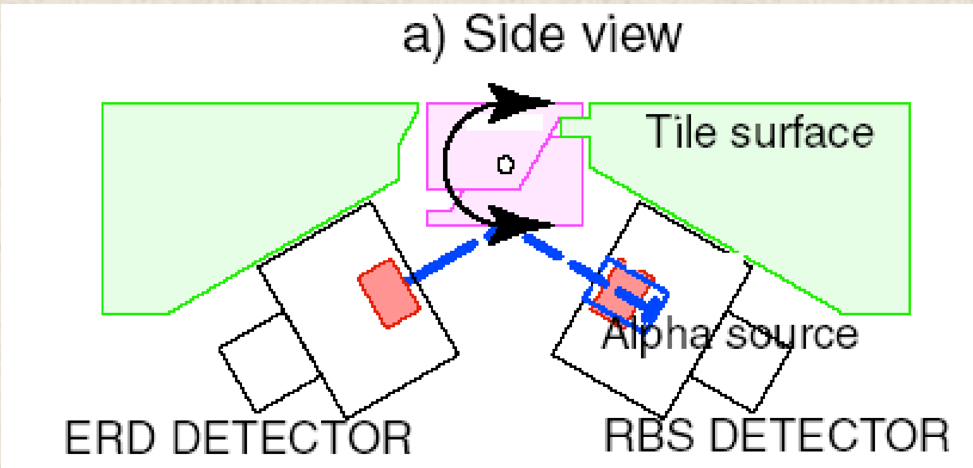


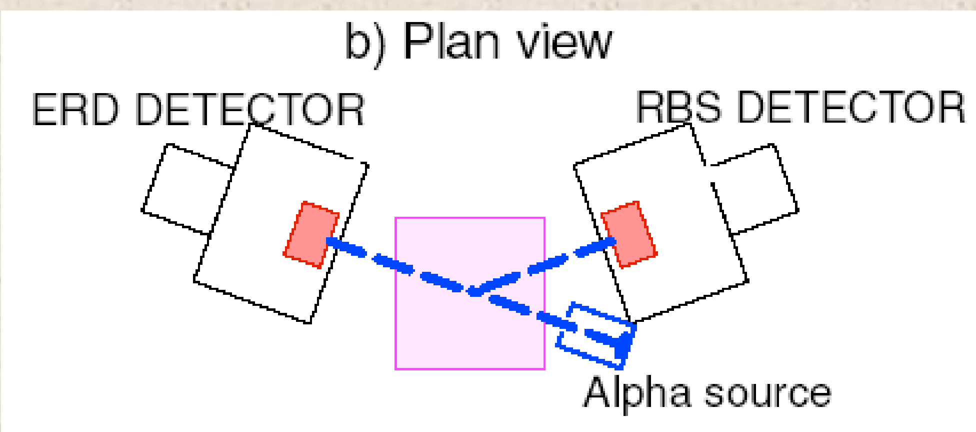
- **Exploit large forward recoil cross-section for high mass projectiles**
- **Same ion-PFC species allows for high current, fast hydrogenic diagnosis**
  - **Case shown: ERD using C-H recoil can measure H profile in ~ 10 ms time**
- **Allows for dynamic study of H implantation, diffusion and release under transient conditions.**

Remote IBA using radio-isotope alpha emitters

- While IBA is the tool of choice for surface diagnosis, how can we provide real-time measurements in a confinement device where we have no access with ion beam?
- Produce an ~mono-energetic alpha ion "beam" using natural alpha emitters
  - Present focus on Po-210 (138 day half-life, E_{alpha}=5.4 MeV
  - Balances need for alpha flux vs. diagnostic lifetime.

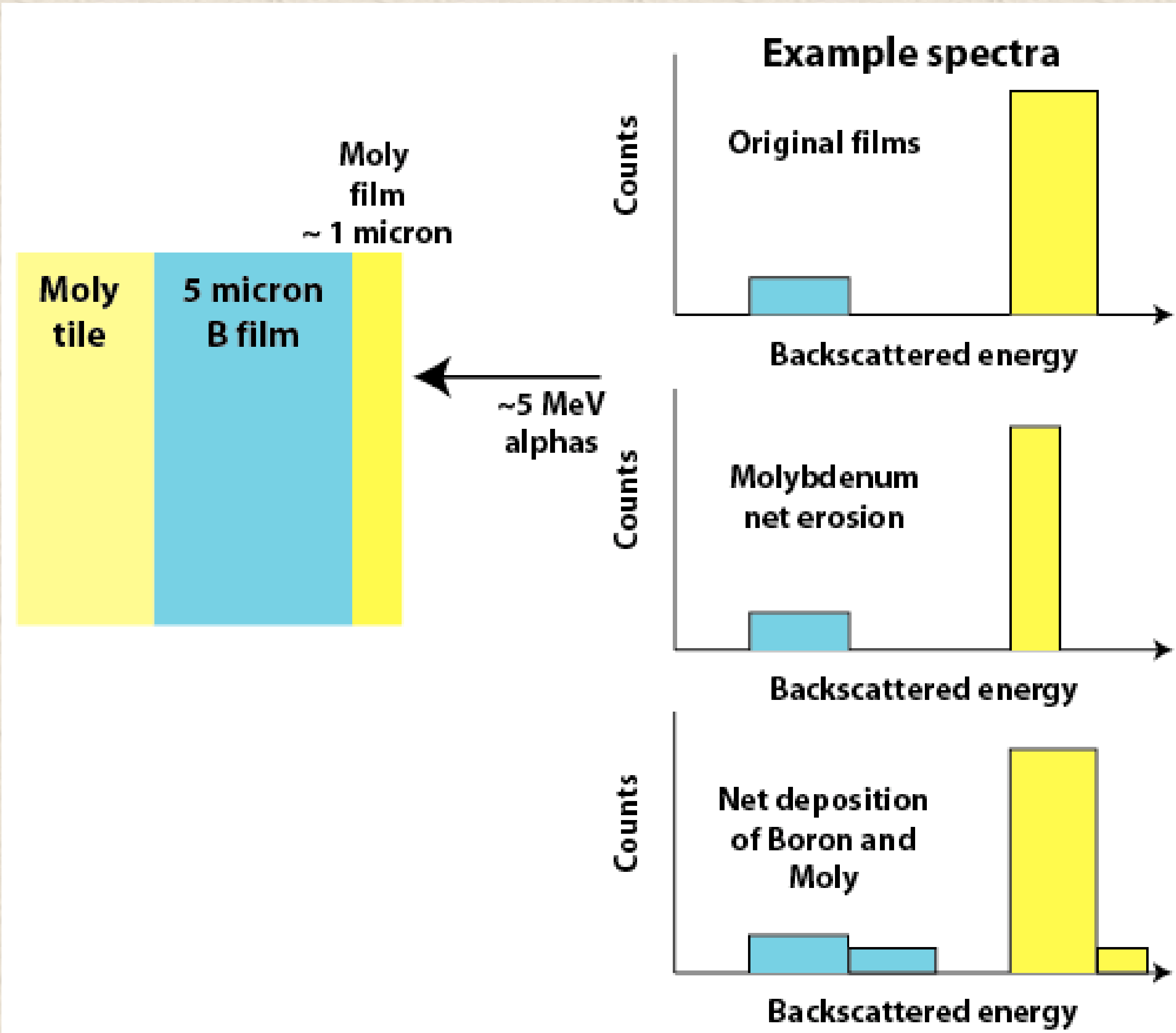
Schematic of Alpha Surface Analyzers (ASA) design for real-time PSI diagnosis in confinement devices





- **Exploit intrinsic magnetic field to rotate surface in/out of contact with main PFC surface.**
  - **Large thermal mass and contact allow for surfaces in high heat flux areas.**
  - **Controls exposure duration of surface in each discharge.**
- **In analysis position, the alpha scattering is detected by s.s. detectors for**
  - **RBS: net erosion/deposition and surface stochiometry**
  - **ERD: Hydrogenic retention over ~ 5 microns.**
- **Po-210 source will allow for surface diagnosis between each shot (~10 minute acquisition time).**

First tests of Alpha Surface Analyzers (ASA) design are being carried out for Alcator C-Mod



- **Multi-layer B/Mo films allow for accurate measurements of net erosion, net deposition and mixed-material analysis in C-Mod.**
- **Other R&D**
  - **Po-210 radiochemistry for film deposition.**
  - **Detector geometry optimization.**